

Gravitational Wave Signals from the First Massive Black Hole Seeds

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ABSTRACT

Recent numerical simulations reveal that the isothermal collapse of pristine gas in atomic cooling haloes may result in stellar binaries of supermassive stars with $M_* \gtrsim 10^4 M_\odot$. For the first time, we compute the in-situ merger rate for such massive black hole remnants by combining their abundance and multiplicity estimates. For black holes with initial masses in the range $10^{4-6} M_\odot$ merging at redshifts $z \gtrsim 15$ our optimistic model predicts that LISA should be able to detect 0.6 mergers per year. This rate of detection can be attributed, without confusion, to the in-situ mergers of seeds from the collapse of very massive stars. Equally, in the case where LISA observes no mergers from heavy seeds at $z \gtrsim 15$ we can constrain the combined number density, multiplicity, and coalescence times of these high-redshift systems. This letter proposes gravitational wave signatures as a means to constrain theoretical models and processes that govern the abundance of massive black hole seeds in the early Universe.

Key words: quasars: supermassive black holes – cosmology: dark ages, reionization, first stars – galaxies: high-redshift – gravitational waves

1 INTRODUCTION

The two aLIGO detectors (Harry & LIGO Scientific Collaboration 2010) observed the first detection of a black hole binary (BHB) on September 14, 2015. This was an unprecedented event and heralded the dawn of gravitational wave (GW) astronomy. The event, GW150914, involved two black holes with masses $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$ coalescing at $z = 0.09^{+0.03}_{-0.04}$ (Abbott et al. 2016). While the sensitivity of aLIGO is limited to the detection of stellar mass sized BHBs, future gravitational wave detectors have the potential to detect more massive systems out to much larger distances and redshifts. LISA (eLISA Consortium et al. 2013) due for launch in 2034 will be able to detect BHB mergers out to $z \gtrsim 20$ opening a window of observation on black hole growth and evolution in the early Universe.

The observation of supermassive black holes (SMBHs) shining as quasars at redshifts greater than 6 (Fan et al. 2003; Mortlock et al. 2011; Venemans et al. 2013; Wu et al. 2015; Bañados et al. 2018) has led to a theoretical challenge in astrophysics. How could such massive objects form so early in the Universe? Stellar mass black hole seeds, similar in mass to those detected by GW150914, are expected to form as the remnants of the very first generation of stars (Heger et al. 2003), however, these seed black holes are also

expected to be born starving with little prospect of growing substantially in the early Universe (Johnson & Bromm 2007; Milosavljević et al. 2009; Alvarez et al. 2009; Smith et al. 2018). Alternatively, a heavy seed model has been proposed that potentially overcomes this early bottleneck. Massive black hole seeds born from the remnants of (super-)massive stars with masses $M_* \gtrsim 10^4 M_\odot$ in atomic cooling haloes (ACHs) have the potential to grow at higher accretion rates (at least initially) compared to lower mass stellar mass seeds. These heavy seeds have been dubbed “Direct Collapse Black Holes” (DCBHs). The deeper potential wells within which they are born are expected to provide the continuous supply of matter required for the black hole to achieve masses close to a billion solar masses by a redshift of six. Determining the actual number densities of heavy seeds is currently an area of intense research (Agarwal et al. 2012; Dijkstra et al. 2014; Habouzit et al. 2016, hereafter A12, D14, H16) and determining what fraction of massive black holes originate from heavy seeds an outstanding problem. Heavy seeds may therefore be the progenitors of all massive black holes, or a small sub-population.

Over the past decade, although increasingly sophisticated simulations and semi-analytic modelling has been employed in an attempt to understand the seed formation mechanisms for SMBHs, the task remains challenging due to lack of observational data. Recent progress on the modelling of supermassive stars (SMSs) suggests that a high accretion rate onto a protostellar core does lead to the formation of an SMS (Hosokawa & Omukai 2008; Hosokawa

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et al. 2013; Woods et al. 2017; Haemmerlé et al. 2018), which would be the ideal progenitor for a heavy seed. In a cosmological context, studies (A12, Agarwal et al. 2014, D14, H16, Chon et al. 2018) have shown that in rare regions of the Universe, where ACHs can remain metal free and the formation of molecular hydrogen is suppressed (due to a strong photodissociating background for example), conditions become conducive to the formation of an SMS. Moreover, SMS forming regions appear to favour the formation of a small number of very massive fragments (Chon et al. 2018; Regan & Downes 2018a,b) all, or at least some of which, can potentially form massive seeds. If the SMSs in these multiple systems form as tight binaries that do not merge until after the stars have collapsed into black holes, then the resulting black hole seeds will have initial masses greater than $10^4 M_{\odot}$, candidates ideal for detection by LISA.

The goal of this paper is to generate templates of DCBH in-situ mergers that can subsequently be compared against LISA detection rates to constrain both the formation scenario and abundance of DCBHs. To achieve this we model the expected number density of DCBH formation sites to constrain the total number of DCBHs expected per unit redshift. We combine this with an estimate of the fragmentation rate within DCBH haloes to obtain the distribution of BHBs and their coalescence times within haloes that host multiple DCBH formation sites. We focus on mergers of heavy seeds ($10^4 M_{\odot} < M_{BH} < 10^6 M_{\odot}$) within the halo in which they are born. We do not consider mergers of black holes as a consequence of galaxy mergers. From the expected number density of DCBH formation haloes and the fragmentation probabilities within these haloes we can quantify the expected rate of DCBH mergers that will be detectable by LISA due to SMS multiplicity.

2 NUMBER DENSITY DISTRIBUTION OF DCBHs

In order to obtain the abundance of DCBH seeds, we use the results of A12, D14 and H16. We focus on two scenarios with $J_c = 30 J_{21}^1$ and $300 J_{21}$ respectively, where J_c is the critical Lyman-Werner (LW) flux required to induce DCBH formation. The exact value of J_c that can facilitate DCBH formation in an ACH is still unknown. What complicates the matter further is that a single value of J_c is not representative of the chemo-thermodynamical processes that lead to the formation of a DCBH, namely the photo-destruction of H^- and H_2 (Wolcott-Green & Haiman 2012; Sugimura et al. 2014; Agarwal & Khochfar 2015; Agarwal et al. 2016). Therefore, we use abundance estimates from the literature and employ two values of J_c as our extreme limits. In doing so we are implicitly assuming that other process may either augment or replace the effect of an external LW field to produce similar results (e.g. streaming velocities, see Tanaka & Li 2014; Hirano et al. 2017; Schauer et al. 2017, or rapid accretion, see Yoshida et al. 2003). Thus, $J_c = 30 J_{21}$ can be viewed as a scenario in which DCBHs are relatively common and would result in a sufficient number of massive seeds for the entire MBH population. On the other hand, $J_c = 300 J_{21}$ would result in a number density of heavy seeds that could only seed a sub-population of massive black holes (perhaps the highest redshift quasars) and can thus be viewed as a scenario where large initial mass black holes are rare. We now describe our steps going from the theoretical estimates of abundance of DCBH seeds to the observed number of events.

¹ J_{21} is the LW flux in units of $10^{-21} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1}$.

Using the models and predictions from the redshift distributions of the newly formed DCBH seeds per unit comoving Mpc^3 found in A12, D14, H16 we calculate a ‘rate’ of formation at time step ‘i’ in units of cMpc^{-3}

$$\left. \frac{dn}{dt dV} \right|_i = \frac{N_{\text{new},i}}{t_i - t_{i-1}} \text{cMpc}^{-3}, \quad (1)$$

where N_{new} is the number of newly formed DCBH sites identified in the simulations for a given value of J_c , and dV denotes the comoving volume normalisation. To get the DCBH formation rate per unit time per unit redshift from any given redshift in the observer’s frame of reference (i.e. as seen at $z=0$), we follow Magg et al. 2016 (eq. 8)

$$\frac{dn}{dz dt} = \frac{4\pi}{1+z} R_z^2 \frac{dR_z}{dz} \frac{dn}{dt dV}, \quad (2)$$

where R_z is the comoving distance at a given redshift.

In Figure 1 we plot the number of DCBH seeds per unit time per unit volume i.e. equation 1, generating a fit using a second order polynomial. The fit is obtained from the estimate for the number density of DCBHs based on $J_c = 30 J_{21}$ (in blue filled circles, A12, D14, and H16), and can be written as

$$\text{Log} \frac{dn}{dt dV} = -11.26t^2 + 13.55t - 13.23 \quad (3)$$

where t is the age of the Universe at which the rate is computed. The number density of pristine ACHs scales approximately as J_{21}^2 (D14, Inayoshi & Tanaka 2015) hence rescaling from $J_c = 30$ to $J_c = 300$ requires a normalisation factor of 10^{-5} . This is shown using the red filled circles. The original data points are shown in red open circles. The scaling reflects the combined effect of the probability distribution function (PDF) of J_c that irradiates ACHs and the abundance of such metal-poor haloes, where the local variation of J_c is accounted for (e.g. Dijkstra et al. 2008, A12, D14, H16). The formation rate initially increases, peaks approximately 500 Myr after the Big Bang, and then decreases as we approach reionisation coinciding with the complete metal enrichment of the Universe and the expected end of DCBH formation.

3 BINARY DCBHs

SMSs have been invoked as possible progenitors of massive black hole seeds (Rees 1978; Eisenstein & Loeb 1995; Bromm & Loeb 2003). Their large initial masses combined with their likely location at the centre of high accretion flow makes them ideal candidates for being the seeds for SMBHs. While the central idea of SMS formation is that a monolithic collapse occurs, recent high resolution simulations have shown that in fact mild fragmentation occurs during the initial collapse (Latif et al. 2013; Becerra et al. 2015; Latif et al. 2016; Chon et al. 2018; Regan & Downes 2018a,b). Typical separations between the massive stars that form are between a few hundred and a few thousand AU while the typical masses of the stars that form is between $10^4 M_{\odot}$ and $10^5 M_{\odot}$. Simulations that can fully resolve the formation of SMSs and follow their progress self-consistently to the formation of a black hole seed are not yet viable, let alone be performed for a significant number of cases. Nonetheless, a small number of fragments are expected and if the fragments are not ejected through three body interactions during the early collapse then BHBs may indeed be commonplace in DCBH host haloes (Regan & Downes 2018b). We constrain our seed models to black holes with masses between $10^4 M_{\odot}$ and $10^6 M_{\odot}$ which tallies with the expected mass range of DCBH seeds (Lodato &

Natarajan 2007; Ferrara et al. 2014). Meanwhile, light seeds born from the remnants of Pop III seeds are not expected to grow quickly enough to achieve masses within this range before a redshift of 9 (Smith et al. 2016). Therefore, any black hole mergers detected at high- z and with seed masses in the DCBH window can be attributed to heavy mass seeds.

After the formation of a BHB, its separation shrinks due to the loss of angular momentum until coalescence of the two black holes occurs. We are primarily interested in BHs with a short coalescence time of $\lesssim 100$ Myr because later merger events that originate from SMS binaries may be confused with events of another origin, such as the merger of central BHs after a galaxy merger (e.g. Sesana et al. 2007, hereafter S07). The two main processes to extract angular momentum from a BHB are GWs and dynamical interactions. The emission of GWs as a mechanism for hardening a binary can only become relevant at sub-AU scales (Peters & Mathews 1963) and hence are not the dominant source of angular momentum loss in this context. Rather, the typical separation of supermassive stellar binaries that form in DC halos are of the order of $100 - 10000$ AU. During the stellar binary evolution, this separation can shrink due to angular momentum loss, especially during a common envelope phase (Belczynski et al. 2017). Unfortunately, we do not yet know the distribution of initial binary separations, the exact stellar binary evolution, or the PDF of coalescence times for SMS remnant BHs. However, the coalescence time PDF for stellar binaries at zero metallicity peaks at short times (< 100 Myr, Hartwig et al. 2016; Belczynski et al. 2017; Inayoshi et al. 2017) or is logarithmically flat (Kinugawa et al. 2014, 2016). This indicates that the majority of binary systems merge shortly after their formation. Also dynamical interactions with stars of a central stellar cluster (Kashiyama & Inayoshi 2016; Hirano et al. 2018) or triple interactions in a small cluster of BHs (Bonetti et al. 2018; Ryu et al. 2018) can harden the BHB and consequently shorten the time until coalescence. For a typical DCBH host halo, Chon et al. (2018) estimated the characteristic time for stars to remove the angular momentum from the BHB system via scattering to be of the order of 10 Myr.

To simplify our calculation we introduce an efficiency parameter f_{bin} . It subsumes all of the internal physical parameters of the BHB formation and merger process that are currently inaccessible to both observation and theory. In our fiducial case we make the strong assumption that all DCBH systems form as binaries and that the binaries merge instantaneously and therefore we set $f_{\text{bin}} = 1$. In cases where the binary fraction is not equal to unity or the merger of the binary DCBH system is long compared to the Hubble time, f_{bin} must be lowered accordingly. Putting more quantitative estimates on the PDF for the extraction of angular momentum and for the multiplicity of heavy seed formation systems is not yet possible and must await more detailed simulations of the formation and evolution of heavy seed models.

4 MERGER RATES FOR DCBHs

In Figure 2 we plot the merger rate of DCBHs in the range $J_c = 30 J_{21}$ to $J_c = 300 J_{21}$. The rates for in-situ mergers of DCBHs are plotted based on equation 2 for different values of both J_c and f_{bin} . The merger rate increases rapidly up to $z \sim 7$ after which it falls off as the conditions required for DCBH formation become less favourable. Overplotted on the same figure are the expected merger rates for massive black holes taken from S07 based on the models of Begelman et al. 2006 (BVR). These models are plotted as black and grey lines according to the feedback model assumed. In S07

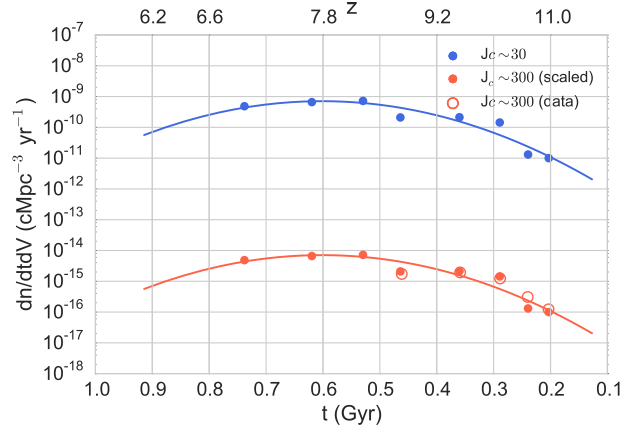


Figure 1. The rate of formation of DCBHs per unit time per unit cMpc^3 , data (circles) and fit (lines). To obtain the fit for $J_c \sim 300$, we scale the data for $J_c \sim 30 J_{21}$ (blue filled circles) by multiplying the data points with 10^{-5} in order to mimic the data for $J_c \sim 300 J_{21}$ (red filled circles). Actual data for $J_c \sim 300 J_{21}$ is shown in red open circles.

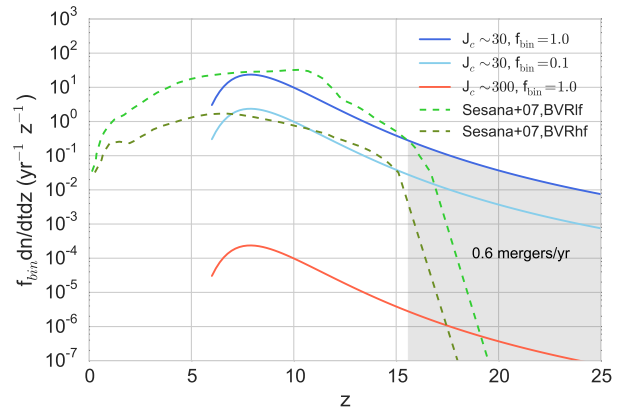


Figure 2. Rates for the merging of BHB from supermassive stellar binaries as a function of redshift compared to the models by S07. We show our results for different values of the critical LW flux and for different values of f_{bin} , which quantifies the fraction of DCBH formation sites that host BHB that merge on a short time scale. Only our optimistic scenario with $J_c \sim 30 J_{21}$ and $f_{\text{bin}} = 1$ can produce a population of BHB mergers at $z \gtrsim 15$ that are clearly distinguishable from other channels of BHB formation. The total rate of such uniquely identifiable BHB mergers is ~ 0.6 per year, highlighted in grey.

the authors, using the BVR model, consider BH mergers as a consequence of galaxy mergers. In the BVR scenario the BHs form via runaway, global dynamical instabilities in metal-free ACHs and gain mass via mergers and gas accretion. BVR argue that gas-rich ACHs with efficient cooling and low angular momentum are prone to the so-called “bars-within-bars” mechanism (Shlosman et al. 1989). Moreover, they argue that the process will naturally end when star formation becomes widespread in the disc. Our model examining the in-situ binary mergers is thus complementary to the BVR model that examines the merger of BHs through galaxy mergers.

From Figure 2 we expect up to ~ 80 mergers per year from supermassive binary stars. In this most optimistic case (solid blue line), with $J_c = 30 J_{21}$ and $f_{\text{bin}} = 1$, the number of mergers per redshift per year are comparable to those of BVR. The number of

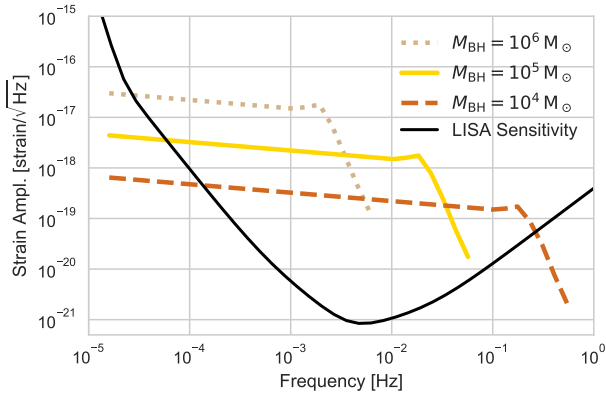


Figure 3. The characteristic strain from the merger of equal mass BHBs at $z = 15$. The black line shows LISA’s expected sky-averaged sensitivity, based on an arm length of 2.5 Mkm (Babak et al. 2017). The other lines give the characteristic strain produced by a merger of two seed black holes, based on the waveforms for non-spinning BHBs by Ajith et al. (2008), which takes into account the inspiral, merger, and ringdown stages of the coalescence. LISA will become sensitive to the merger at a frequency, $f \gtrsim 10^{-4}$ Hz.

mergers reduces linearly with f_{bin} (light blue line). In both models the majority of mergers occur around $z \sim 10$ and are therefore not distinguishable from each other. Only at $z \gtrsim 15$ where our proposed channel dominates, with detection rates of ~ 0.6 per year, can we distinguish between the models for in-situ mergers compared to galaxy mergers. In the BVR model detections beyond $z \sim 15$ should be exceedingly rare due to the fact that seeds must form and their host galaxy must then merge with another galaxy before a massive BHB merger process can begin. In our model the BHB binary is available for merging instantaneously and hence the model extends to higher redshift. In a ten year LISA mission our model predicts 6.1 ± 2.5 BHB mergers with $z \gtrsim 15$. For $J_c = 300$ the number of mergers expected drops by a factor of 10^5 .

5 DETERMINING THE DCBH NUMBER DENSITY WITH LISA

The current uncertainties surrounding the DCBH model mean that we cannot break the degeneracy between the product of the DCBH number density (modelled here by assuming a critical LW field J_c) and f_{bin} . As discussed in detail above f_{bin} accounts for the fraction of DCBH systems that host a binary that merges to produce a gravitational wave signal. A detection of BHB mergers at $z \gtrsim 15$ could constrain the product of the DCBH number density and f_{bin} . As discussed in §4 over the 10 year lifetime of LISA we expect 6.1 ± 2.5 events. Further numerical modelling of the hosts of DCBH systems will be required to provide greater insight into the exact value of f_{bin} . Nonetheless, by employing an optimistic value of $f_{\text{bin}} = 1$ we can estimate the expected detection rates from LISA.

LISA is ideally suited for detecting the gravitational wave signal from black hole masses in the range of $\sim 10^4 \leq M_{\text{tot}}/M_{\odot} \leq 10^6 M_{\odot}$ at redshifts up to $z \sim 20$ with signal-to-noise ratio of $\text{SNR} > 10$ (Amaro-Seoane et al. 2013; Babak et al. 2017). Predicting the precision of the inferred luminosity distance (and hence redshift) requires numerical simulations (Porter 2015) or a detailed fisher matrix analysis (Klein et al. 2016), which is beyond the scope of this paper. In addition, the uncertainty on the luminosity distance, and therefore on the inferred event redshift, due to weak lensing is

23% at $z = 15$ (Tamanini et al. 2016). In Figure 3 we plot the characteristic strain amplitude for black hole seed mergers of two equal mass black holes at $z = 15$. The LISA sensitivity is shown by the black curve using a LISA arm length of 2.5 million kilometers connected by six laser links (Babak et al. 2017). Noise in the detector is accounted for following the analytical considerations of Babak et al. (2017) that includes noise contributions for low-frequency noise, local interferometer noise and shot noise. The coloured lines illustrate the strain evolution based on waveforms for equal-mass, non-spinning BHBs (Ajith et al. 2008). We focus on equal-mass BHBs since the mass ratio $q = M_1/M_2$ with $M_1 < M_2$ contributes only as a second-order correction to the coalescence time and strain amplitude compared to an equal-mass binary with the same total mass. The LISA Pathfinder mission has spectacularly demonstrated the capabilities of the hardware with obtained sensitivities below the estimates for LISA. Therefore, our sensitivity curve can be seen as a conservative limit (Armano et al. 2018).

In §4 we discussed the merger rates of DCBH finding that even under optimistic assumptions, the number of detections that can clearly be assigned to the merger of SMS remnant BHBs is of order unity. We therefore turn the question around and ask what constraining power lies in the non-detection of such sources at $z > 15$. Following Poisson statistics, the probability of a non-detection is $p(0) = \exp(-\lambda)$, where λ is the expectation value of detections over the observation time t , with $\lambda = 0.6t/\text{yr}$ in our optimistic model. If there is no detection, $1 - p(0)$ can be interpreted as the likelihood that this non-detection is representative of the theoretical model. Requiring a statistical significance of 95% (2σ) we derive $\lambda = 3$. Phrased differently, after five years of observations and no detections at $z > 15$ we can already exclude our optimistic model with 95% certainty. After 10 years of non-detections, we can rule out the DCBH abundance model that hints at their ubiquity ($J_c = 30$) with 3σ certainty, and set an upper limit of $f_{\text{bin}} < 0.5$ (0.18) for $J_c = 30 J_{21}$ at the 2σ (1σ) level.

6 SUMMARY

Recent studies have been able to derive a range of massive black hole seed number densities, depending on the modelling of realistic physical conditions that lead to their formation. By choosing two extreme values of J_c , the critical LW flux, which is often used to parameterise massive seed formation, we bracket a range of DCBH scenarios ranging from ubiquitous to rare. Recent, high resolution, numerical simulations of the formation of the first SMBHs in ACHs have suggested that SMSs form in systems with multiple siblings. By assuming that these systems then go on to host binary black holes that subsequently merge, we are able to derive an in-situ merger rate per unit redshift for these black holes. We find the merger rate increases rapidly at high redshift peaking at a redshift of $z \sim 7$ before declining again as DCBH formation ceases (see Figure 2). This model can be directly compared to the model of S07 for similar mass seeds with mergers occurring due to the merger of their host galaxies. While the number of mergers is comparable at redshifts around $z \sim 10$, based on optimistic assumptions for the binary fraction and coalescence times our model contains significantly more mergers at $z \gtrsim 15$ as we only probe the number of in-situ binary mergers in a halo.

We find that if LISA’s detector sensitivities can match the design sensitivities then massive seeds will be detectable by LISA up to a year before the actual merger with 6.1 ± 2.5 mergers at $z \gtrsim 15$ expected in a ten year mission lifetime. Moreover, if more

than 1 merger is detected at $z \gtrsim 15$ our binary massive black hole model will be verified with constraints placed on the number density - f_{bin} model (where f_{bin} encompassed the fraction of heavy seeds that form binaries and merge with short coalescence times). Even in the case where no detections are made at $z \gtrsim 15$ we will be able to constrain the number density - f_{bin} model with precision that scales with the mission lifetime. If these statistics can be matched with improvements to the IMF, binary fraction, and coalescence times of massive seed black holes then strong constraints on the DCBH number density will follow.

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REFERENCES

- Abbott B. P. et al., 2016, *Physical Review Letters*, 116, 061102
- Agarwal B., Dalla Vecchia C., Johnson J. L., Khochfar S., Paardekooper J.-P., 2014, *MNRAS*, 443, 648
- Agarwal B., Khochfar S., 2015, *MNRAS*, 446, 160
- Agarwal B., Khochfar S., Johnson J. L., Neistein E., Dalla Vecchia C., Livio M., 2012, *MNRAS*, 425, 2854
- Agarwal B., Smith B., Glover S. C. O., Natarajan P., Khochfar S., 2016, *Monthly Notices of the Royal Astronomical Society*, stw929
- Ajith P. et al., 2008, *Phys. Rev. D*, 77, 104017
- Alvarez M. A., Wise J. H., Abel T., 2009, *ApJL*, 701, L133
- Amaro-Seoane P. et al., 2013, *GW Notes*, Vol. 6, p. 4-110, 6, 4
- Armano M., et al., 2018, *Phys. Rev. Lett.*, 120, 061101
- Bañados E. et al., 2018, *Nature*, 553, 473
- Babak S. et al., 2017, *Phys. Rev. D*, 95, 103012
- Becerra F., Greif T. H., Springel V., Hernquist L. E., 2015, *MNRAS*, 446, 2380
- Begelman M., Volonteri M., Rees M., 2006, *MNRAS*, 370, 289
- Belczynski K., Ryu T., Perna R., Berti E., Tanaka T. L., Bulik T., 2017, *MNRAS*, 471, 4702
- Bonetti M., Haardt F., Sesana A., Barausse E., 2018, *MNRAS*, 477, 3910
- Bromm V., Loeb A., 2003, *ApJ*, 596, 34
- Chon S., Hosokawa T., Yoshida N., 2018, *MNRAS*
- Dijkstra M., Ferrara A., Mesinger A., 2014, *MNRAS*, 442, 2036
- Dijkstra M., Haiman Z., Mesinger A., Wyithe J. S. B., 2008, *MNRAS*, 391, 1961
- Eisenstein D. J., Loeb A., 1995, *ApJ*, 443, 11
- eLISA Consortium et al., 2013, *ArXiv e-prints* 1305.5720
- Fan X. et al., 2003, *The Astronomical Journal*, 125, 1649
- Ferrara A., Salvadori S., Yue B., Schleicher D., 2014, *MNRAS*, 443, 2410
- Habouzit M., Volonteri M., Latif M., Dubois Y., Peirani S., 2016, *MNRAS*, 463, 529
- Haemmerlé L., Woods T. E., Klessen R. S., Heger A., Whalen D. J., 2018, *MNRAS*, 474, 2757
- Harry G. M., LIGO Scientific Collaboration, 2010, *Classical and Quantum Gravity*, 27, 084006
- Hartwig T., Volonteri M., Bromm V., Klessen R. S., Barausse E., Magg M., Stacy A., 2016, *MNRAS*, 460, L74
- Heger A., Fryer C. L., Woosley S. E., Langer N., Hartmann D. H., 2003, *ApJ*, 591, 288
- Hirano S., Hosokawa T., Yoshida N., Kuiper R., 2017, *Science*, 357, 1375
- Hirano S., Yoshida N., Sakurai Y., Fujii M. S., 2018, *ApJ*, 855, 17
- Hosokawa T., Omukai K., 2008, *Massive Star Formation: Observations Confront Theory ASP Conference Series*, 387, 255
- Hosokawa T., Yorke H. W., Inayoshi K., Omukai K., Yoshida N., 2013, *ApJ*, 778, 178
- Inayoshi K., Hirai R., Kinugawa T., Hotokezaka K., 2017, *MNRAS*, 468, 5020
- Inayoshi K., Tanaka T. L., 2015, *MNRAS*, 450, 4350
- Johnson J. L., Bromm V., 2007, *MNRAS*, 374, 1557
- Kashiyama K., Inayoshi K., 2016, *ApJ*, 826, 80
- Kinugawa T., Inayoshi K., Hotokezaka K., Nakauchi D., Nakamura T., 2014, *MNRAS*, 442, 2963
- Kinugawa T., Miyamoto A., Kanda N., Nakamura T., 2016, *MNRAS*, 456, 1093
- Klein A. et al., 2016, *Phys. Rev. D*, 93, 024003
- Latif M. A., Schleicher D., Hartwig T., 2016, *MNRAS*, 458, 233
- Latif M. A., Schleicher D., Schmidt W., Niemeyer J. C., 2013, *MNRAS*, 436, 2989
- Lodato G., Natarajan P., 2007, *MNRAS: Letters*, 377, L64
- Magg M., Hartwig T., Glover S. C. O., Klessen R. S., Whalen D. J., 2016, *MNRAS*, 462, 3591
- Milosavljević M., Bromm V., Couch S. M., Oh S. P., 2009, *ApJ*, 698, 766
- Mortlock D. J. et al., 2011, *Nature*, 474, 616
- Peters P. C., Mathews J., 1963, *Physical Review*, 131, 435
- Porter E. K., 2015, *Physical Review D*, 92
- Rees M. J., 1978, *Phys. Scr.*, 17, 193
- Regan J. A., Downes T. P., 2018a, *MNRAS*, 475, 4636
- Regan J. A., Downes T. P., 2018b, *ArXiv e-prints* 1803.04527
- Ryu T., Perna R., Haiman Z., Ostriker J. P., Stone N. C., 2018, *MNRAS*, 473, 3410
- Schauer A. T. P., Regan J., Glover S. C. O., Klessen R. S., 2017, *MNRAS*, 471, 4878
- Sesana A., Volonteri M., Haardt F., 2007, *MNRAS*, 377, 1711
- Shlosman I., Frank J., Begelman M. C., 1989, *Nature*, 338, 45
- Smith A., Bromm V., Loeb A., 2016, *MNRAS*, 460, 3143
- Smith B., Regan J., Downes T., Norman M., O'Shea B., Wise J., 2018, *ArXiv e-prints*: 1804.06477
- Sugimura K., Omukai K., Inoue A. K., 2014, *MNRAS*, 445, 544
- Tamanini N., Caprini C., Barausse E., Sesana A., Klein A., Petteau A., 2016, *J. Cosmol. Astropart. Phys.*, 4, 002
- Tanaka T. L., Li M., 2014, *MNRAS*, 439, 1092
- Venemans B. P. et al., 2013, *ApJ*, 779, 24
- Wolcott-Green J., Haiman Z., 2012, *MNRAS: Letters*, 425, L51
- Woods T. E., et al., 2017, *ApJ*, 842, L6
- Wu X.-B. et al., 2015, *Nature*, 518, 512
- Yoshida N., Abel T., Hernquist L., Sugiyama N., 2003, *ApJ*, 592, 645